Decade-scale change and connectivity through phytoplankton: Monterey Bay looks into the Pacific

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ABSTRACT --- Monterey Bay has changed since the 1990s. Prior to the strong 1997-1998 El Niño, Monterey Bay was warmer, its nutrients were deeper, and phytoplankton production was dominated by spring and early summer blooms of centric diatoms. During the 2000s, Monterey Bay has been cooler, its nutrients shallower, and total primary production much higher. Centric diatoms still bloom during early summer as in the 1990s, but pennate diatom and dinoflagellate blooms are much stronger than previous in late summer and fall. In some years pennates dominate, and in others dinoflagellates dominate. These changes in phytoplankton (i) production, (ii) seasonality and (iii) dominant taxa must have strong affects on zooplankton, fish and mammals, all of which are ultimately dependent on phytoplankton for food.

A portion of the increased phytoplankton growth sinks and decays, increasing CO2 and acidity. In the central Pacific, similar but weaker changes have been attributed to the ocean's absorption of man-made CO2. In Monterey Bay we observe a stronger increase due to the combined effects of both processes. The decay also decreases subsurface oxygen, which may favor range expansion by the suboxia-tolerant jumbo squid.

These changes are part of basin-wide climactic fluctuation. During the 2000s, the Eastern and Equatorial Pacific have been cool --- just as we observe in Monterey Bay --- opposite the central subtropical gyres and Western Pacific, which have been warm. While these changes are widespread and important, their causes remain mostly unknown. Tiny Monterey Bay, looking out into the Pacific, lets us observe change in this vast system.

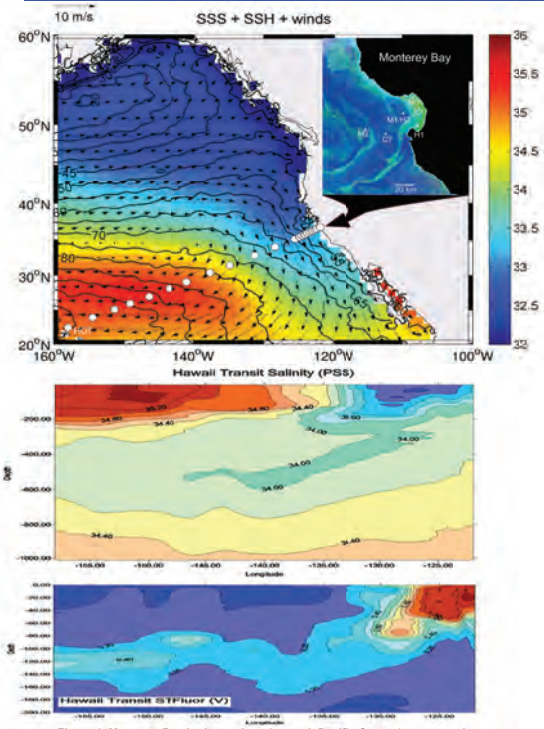

Figure 1. Monterey Bay looks out into the north Pacific Ocean (upper panel and inset). The low salinity (**blue**) California Current flows southwards past the Bay as the eastern margin of the North Pacific subtropical gyre, before transitioning offshore to salty (**red**) central Pacific surface waters. Cruise stations (**upper panel, white circles**) show the California Current (**middle panel**) to be about 300m deep and 1300km broad. Interaction of California Current flow with the earth's rotation causes isolines to lift (tilt upwards) towards shore; this 'isopycnal tilting' also lifts the nutricline into the euphotic zone. Thus isopycnal tilting affects nutrient supply to the nearshore euphotic zone, increasing the sensitivity of Monterey Bay ecosystems to changes in subtropical gyre flow. Fluorescence data show the strong effects of isopycnal tilting and nutricline shoaling on nearshore phytoplankton biomass (**bottom panel**). Isopycnal tilting occurs over larger spatial and longer temporal scales than coastal upwelling.

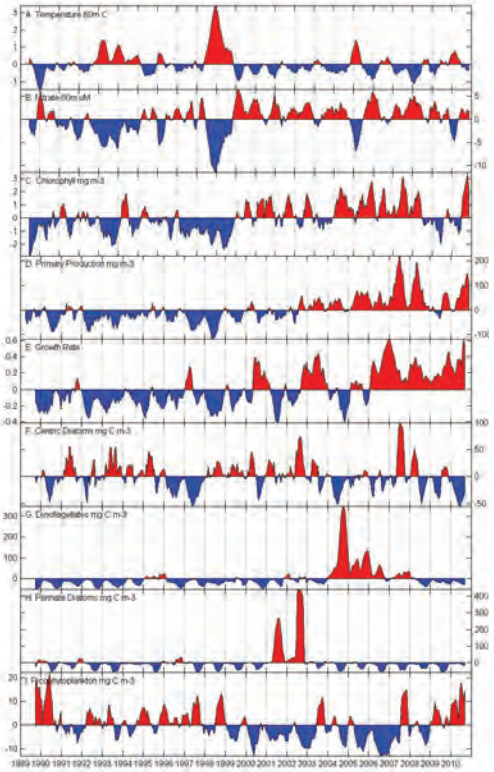

Figure 2. Does isopycnal tilting affect Monterey Bay ecosystems over multiyear periods? Monterey Bay cruise stations (**Fig. 1, upper panel inset**) have been occupied by ship each 2-3 weeks for the past two decades, and anomaly time series (deseasonalized and smoothed differences from mean conditions) show that in the 2000s, after the strong 1997-1998 El Niño, the environment changed. 60m temp decreased and 60m nitrate increased (**Fig. 2A-B**), indicating isopycnal tilting and lifting of the thermocline and nutricline, as described under Fig. 1. As consequences of a shallower nutricline, surface chlorophyll, primary production and phytoplankton growth rate all increased substantially (**Fig. 2C-E**). Suprisingly, the abundance of centric diatoms --- the classic 'keystone' phytoplankton taxon of upwelling systems --- has not increased in the 2000s (**Fig. 2F**). Instead, Dinoflagellates and pennate diatoms have exhibited dramatic blooms in some years but not others (**Fig. 2G-H**). Picophytoplankton, a diverse group characteristic of the open ocean, have been less abundant in the 2000s (**Fig. 2I**).

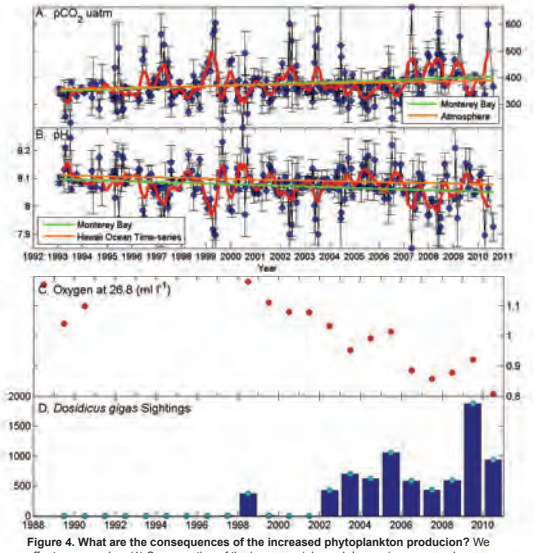

Figure 4. What are the consequences of the increased phytoplankton producion? We offer two examples: (1) Some portion of the increase sinks and decays in a process known as the 'biological pump', and the decay increases water column pCO2 and acidity (acidity is negative pH). In spite of considerable seasonal and other variability, these increases are measurable (**Fig. 4A-B, blue dots & green lines**). Off Hawaii, similar but weaker increases have been attributed to increasing atmospheric CO2 (Fig. 4A, **orange line**). The stronger increases in Monterey Bay (**green lines**) are due to the combined effects of both processes; (2) An increased biological pump also depletes subsurface oxygen (**Fig. 4C**), which may have favored range expansion by the suboxia-tolerant jumbo squid, *Dosidicus gigas* (**Fig. 4D**). Increased phytoplankton production in the 2000s must also increase food supplies for krill, fish, birds and mammals.

SUMMARY POINTS

- Interaction between flow and the earth's rotation lifts the thermocline at the margins of the north Pacific subtropical gyre. Increases in flow increase this 'isopycnal tilting'.
- In the nearshore California Current, isopycnal tilting can lift the nutricline into the euphotic zone, increasing nutrient supply to coastal ecosystems. Coastal California ecosystems are thus sensitive to changes in California Current and north Pacific subtropical gyre flow.
- Monterey Bay has had a shallower thermocline and nutricline in the 2000s relative to the 1990s. As consequences, phytoplankton chlorophyll, primary production and growth rate have all been higher in the 2000s.
- Curiously, centric diatoms --- the hallmark phytoplankton taxon of coastal upwelling systems --- have not been more abundant in the 2000s. Instead, dinoflagellates and pennate diatoms have been much more abundant in late summer and fall of some years. Picophytoplankton have been less abundant in the 2000s.
- Due in part to sinking and decay of the increased productivity, water column pCO2 and acidity have increased. Subsurface oxygen has also decreased, possibly favoring range expansion by the suboxia-tolerant jumbo squid, *Dosidicus gigas*. Other ecosystem effects are likely.
- A global SST analysis shows strong cooling in the NE Pacific after 1997-98. This cooling likely reflects increased California Current flow, isopycnal shoaling, and nutrient supply to Monterey Bay ecosystems, producing the strong ecosystem changes observed in the 2000s.

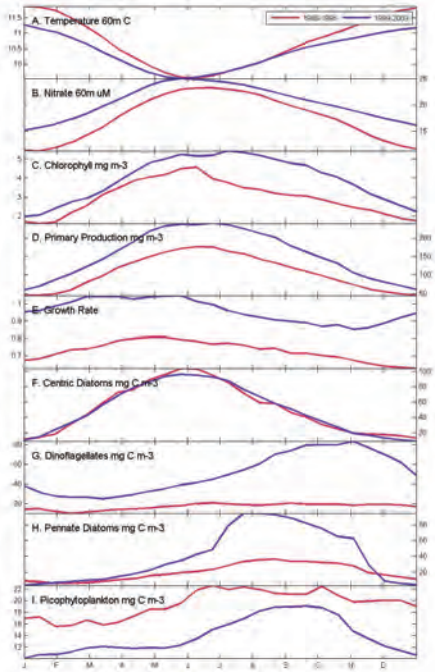

Figure 3. What do average years in each decade look like? During the 2000s, 60m temperature has been cooler and nitrate higher all year (**Fig. 3A-B**). Chlorophyll, primary production and growth rate have also been higher all year (**Fig. 3C-E**), almost certainly due to increased nitrate supply. The taxon-specific differences between decades are unexpected and strong. Centric diatom abundance did not increase but is essentially the same between decades (**Fig. 3F**), whereas in the 2000s both dinoflagellates and pennate diatoms have been much more abundant in late summer or even fall (**Fig. 3H-I**). In some years dinoflagellates and in others pennates dominate (Fig. 2G-H). Oceanic picophytoplankton have been less abundant in the 2000s (**Fig. 3I**).

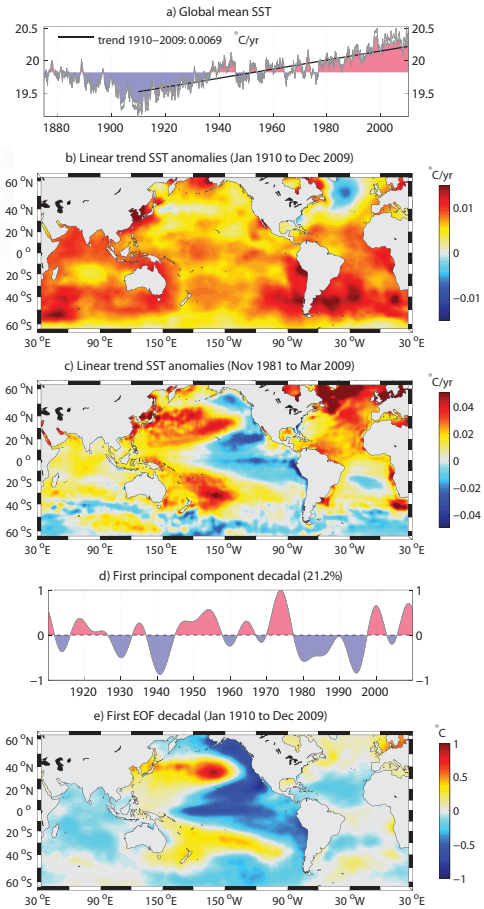

Figure 5. Are the Monterey Bay changes connected to the north Pacific basin? A global SST record (ICOADS) shows warming since 1910 (**Fig. 5A**) distributed fairly evenly over the world's oceans (**Fig. 5B**). However when the temperature change since 1981 is plotted, a spatial signature emerges, with cooling in the NE Pacific (**Fig. 5C**). If the SST record is detrended and filtered to remove sub-decadal variability, then subjected to EOF analysis, a similar 'decadal' pattern emerges. The temporal evolution (1st PC, **Fig. 5D**) shows that global SST changed around 1997-98, and the spatial distribution of this change (1st EOF, **Fig 5E**) indicates strong cooling for the NE Pacific. This analysis suggests a cooling NE Pacific with increased California Current flow and isopycnal tilting, just as we observe in Monterey Bay.